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INFLUENCE OF MECHANICAL TREATMENT ON SOME RHEOLOGICAL PROPERTIES OF BUTTER

by

ILIJA VASIC

A THESIS

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled

INFLUENCE OF MECHANICAL TREATMENT

ON SOME RHEOLOGICAL PROPERTIES OF BUTTER

submitted by Ilija Vasic in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

Mechanical treatment of butter with a completely formed structure has a definite influence on some of its rheological properties. The type of mechanical treatment is not important as long as it induces tangential stresses that are high enough (i.e. above the yield point) to destroy the initial structure of the butter.

Butter exibits thixotropy which manifests itself in a partial recovery of the original structure after mechanical working. It was shown that under normal conditions the recovery of structure is incomplete which indicates that during mechanical working some irreversible changes take place. This might be a consequence of the partial disintegration of large crystals in butter.

Solid fat content is not the only factor that influences hardness. By comparison of hardness values before and after working for two types of butter (churned and continuously made), it was shown that the secondary structure, i.e. the three-dimensional crystal network contributes to the hardness of butter.

The extrusion of butter has a distinct advantage over other types of mechanical working for the evaluation of some rheological properties, because the conditions of the experiments may be completely controlled and adjusted.

A formula was derived for determination of the hardness from penetration values obtained by means of a cone penetrometer.

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INFLUENCE OF MECHANICAL TREATMENT ON SOME RHEOLOGICAL PROPERTIES OF BUTTER

INTRODUCTION

General considerations

Newtonian viscous fluids and Hookean elastic solids are the representatives of the two large groups into which all substances have been divided according to their physical properties. Approximately half a century ago, it was recognized that there is a third, even larger group of substances, which is intermediate between the first two. The common name used to describe this group is "plastic substances".

Plasticity can be defined as a property that enables a material to be deformed continuously without breaking up during the application of a stress (24).

The physical properties of Newtonian fluids and Hookean solids were studied extensively and now it is possible to predict the behaviour of such substances under the influence of external forces. Although many approximations and simplifications during the development of theoretical equations are made, there is a high degree of agreement between theory and practice in the case of these materials. The main reason

for this is an isotropy of these substances which is a consequence of microhomogenity or, in other words, of small dimensions of the particles. Also, the interparticle forces are predominantly of one kind and therefore it is less difficult to express the behaviour of such substances mathematically.

A different situation prevails in the case of plastic substances. Almost all plastic substances have a complex chemical composition, i.e., they contain a variety of elements in the molecule and usually have a high molecular weight, and therefore the particles of these substances are large - often called macromolecules. One can not expect a high degree of isotropy if a substance is composed of large, irregularly-shaped particles.

In many cases, plastic substances contain both solid and liquid phase simultaneously, which contributes a further complication to an already complex situation.

A separate group of plastic substances is the group which consists of organic materials. This group appears to be the most difficult to study because of the variation in chemical composition even of one single substance, as a consequence of different biosynthetic processes of this particular substance. Sometimes, a slight variation in chemical composition does not influence the physical properties of a plastic substance very much, but in many cases the physical properties may be changed considerably.

The physical structure of the butter

Factors having a direct influence on the structure of butter can be divided into three main groups:

(i) The chemical composition and structure of the materials from which the butter is made.

(ii) The technological procedure by which the butter is manufactured.

(iii) The treatment of butter after production.

The chemical composition of milk or cream is very important, particularly that of milk fat, because the fatty acid and glyceride composition may have a considerable influence on structure and consistency of butter.

The structure of milk fat should be taken into consideration as a factor influencing consistency of butter. Milk fat is present in milk and cream in a disperse form as fat globules with a protective surface layer. This form results in different crystallization conditions in the liquid fat than in free fat as it is present in the continuous method of buttermaking, or in the case of reconstitution of butter from butter-oil and skim milk.

Manufacturing method also has a large influence on the consistency of butter by changing the degree of dispersion of the butter components: fat globules are broken up and a certain amount of liquid fat is released, which allows the formation of butter granules; the

dispersion of the water phase is changed and, finally, the oil-in-water emulsion (cream) is completely changed into a water-in-oil emulsion (butter).

This complex change is accompanied by partial crystallization of the fat phase. This transformation is, therefore, highly temperature dependent, and the temperature treatment during production influences the consistency of butter. The structure formed immediately after manufacturing is unstable and, depending on further treatment, different final structures will be obtained. Storage temperatures may considerably influence the speed and degree of the stabilization of butter, i.e., the formation of a new structure in which the crystallized part will be in a thermal equilibrium with the liquid phase of fat.

Mechanical working also has a certain influence on the structure of butter because of a definite change in the three-dimensional crystal network after working.

REVIEW OF THE LITERATURE

Solid and liquid state of plastic fats

All edible lipids may be classified into two main groups: oils and fats. By definition, oils are liquid at room temperature (usually 20°- 25°C), and fats are solid at the same temperature. The terms "liquid" and "solid" need some explanation, because in the case of plastic fats there is no sharp boundary between these two states which are easily distinguished in the case of Newtonian fluids and Hookean solids.

The liquid state of plastic substances can be defined as the state in which the substance will flow with an easily detectable speed, under the influence of the force of gravity. This definition can be generally accepted, with a few exceptions such as asphalt, tar, pitch, and others. Asphalt, for instance, appears as a solid substance, but when left for a long time (several days or weeks) at a favourable temperature it will flow, although in a limited manner; at the end of that period of time it will assume a different shape, i.e., it will be permanently deformed through the flow under the influence of the force of gravity.

The liquid state of an edible fat - oil, on the other hand, is not very complex from the physical point of view. Most oils when completely liquid, i.e., without solid particles suspended in them,

follow reasonably closely the properties of Newtonian fluids.

The common definition of a fluid can be applied also to the liquid state of a plastic fat. According to this definition, a fluid is a substance that can be deformed by even the slightest stresses. The tangential stresses between adjacent particles, or layers, are proportional to the velocity of deformation or velocity gradient, and stresses disappear when the motion is stopped (38).

The true solid state of a plastic fat occurs at temperatures far below 0°C, if one understands that the term "solid state" means that there is no liquid material present in the fat. In everyday practice, the term "solid fat", or simply "fat", is used in a much broader sense and if one says that such fat is solid at room temperature, it can happen that this particular fat contains more than fifty percent liquid phase, but it still appears and behaves as a solid substance.

The so-called solid state of a plastic substance, including fats, can be defined as the state in which the substance will not flow under the influence of the force of gravity.

There is also another well known definition of the solid state of a plastic substance. The solid substance, no matter how plastic, requires a certain magnitude of the tangential stress, necessary to induce a permanent deformation. When external forces causing deformation are removed, the stresses will remain and will act to restore the initial shape of the body before deformation (3).

Rheological properties of plastic fats

Only a few characteristics are sufficient for the description of the physical properties of Newtonian fluids and Hookean solids. Density, viscosity, and surface tension are the main characteristics of Newtonian viscous liquids; while density, modulus of elasticity, and shear modulus, besides some other mechanical properties (e.g., rupture strength, relative strain, impact strength) are the main characteristics of Hookean elastic solids.

Many difficulties arise in describing the physical or rheological properties of plastic fats. One of the most serious is a lack of adequate terminology for the definition of several properties which, in combination, provide a complete description of the rheological properties of a plastic fat. Many rheologists use different terms to describe the same property of a plastic substance, and this undoubtedly leads to misunderstanding.

Another important factor which does not contibute to a better understanding of rheological properties is a lack of absolute units for expressing the data obtained by instrumental measurements. This is a consequence of the fact that there are no standard methods and standard instruments for measurements of physical properties of plastic substances. Some methods have been standardized but are not widely accepted.

Even much simpler substances - metals for instance - show different values for the same property when tested by means of different instruments and methods, and it seems quite logical that more complex materials, such as the plastic fats, will show greater variations depending

on the instruments and methods used for determination of their properties.

A short review of the various terms used for the description of the rheological properties of butter will be given to avoid misunderstanding in the remainder of the text.

Consistency. This term is used, in a broad sense, for describing the sum of all rheological properties; consistency can be considered as an expression of the total rheological properties (1, 14). Sometimes, this term is used instead of hardness or softness (2, 4, 55, 66), or it is substituted by an ill-defined expression "body" (19, 31, 39). The term body seems to be widely used in practice while the term consistency predominates in scientific papers.

Consistency can be described as the property of a substance which enables the material to resist a permanent or plastic change in shape and it is determined by the flow-force or flow-stress relation (25, 59). It is, therefore, clearly distinct from rigidity - a property involving resistance to elastic change of shape. Consistency is a property which produces a general impression of resistance to flow (62).

Viscosity is defined as a resistance to flow of Newtonian fluids and for such reason, consistency is sometimes replaced by the terms "apparent viscosity" (35) and "consistency index" (2, 71), terms which are not incorrect, but rather, incomplete.

Consistency is a qualitative characteristic of a substance and therefore can be considered as an attribute expressing the sum of several physical properties and having no definite dimensions (64).

Structure. Can be defined as the manner in which the components of butter (crystals, free oil, fat globules, moisture droplets, air bubbles) are distributed and arranged, i.e., as an "architecture" of butter (41). It is also a qualitative, dimensionless characteristic.

Texture. Is often used as a term for description of the visual appearance of the substance, as it is seen by the naked eye (41). Microstructure is a term used when the observation is made by a microscope. Like the two previous terms, texture is also a qualitative characteristic with no definite dimensions.

Hardness. This is one of the most significant physical properties of plastic fats because it is an important factor of consistency. But, as was pointed out before, there are difficulties in giving a precise definition of hardness. Several definitions can be found in the literature, the most common being that hardness is resistance to deformation (6), or even resistance to shear (19). These definitions do not seem to be precise enough, because there are several kinds of stresses which may cause quite different deformations, while the shear modulus is known as a measure of the resistance to shear.

There is a precise definition of hardness of metals and there is no reason why the same definition should not be applied in the case of plastic fats. Therefore, hardness can be defined as the property of a material to resist the penetration of an external body into it. The absolute unit for expression of hardness values is the magnitude of the force required to make the indentation, divided by the area of impression, i.e., lb./sq. in., or kg/cm^2, depending on the

system of units used.

If such a definition should be accepted for description and determination of the hardness of plastic fats, it would probably help decrease the lack of uniformity of results. Much time and effort is now wasted in trying to correlate the data obtained for a single physical property by different methods and instruments.

Apparent viscosity. The term viscosity should not be used when dealing with non-Newtonian fluids or plastic materials because this term is already used to define a constant ratio of the velocity of deformation (velocity gradient) and the shearing stress of Newtonian fluids. In the case of plastic materials, the ratio between the rate of shear and the shearing stress is not constant but depends on rate of shear. For this reason several terms were proposed, such as: internal friction (5, 64), structural viscosity (59, 62, 64), and apparent viscosity (18, 71). All of these are self-descriptive, and they can all be used. The term apparent viscosity has the advantage of emphasizing the fact that viscosity of non-Newtonian fluids is not constant. Apparent viscosity has the same dimension as the viscosity of Newtonian fluids, as well as having the same unit: poise or centipoise - 1 poise being equal to 1 dyne $\times$ sec/cm^2.

Spreadability. Is defined as the spreading capacity of butter and this term comprises not only the property of the butter itself, but also the adhesion of the surface on which the butter is being spread.

Firmness. Is sometimes used as a synonym for hardness, or is used to describe resistance to deformation of the butter under the influence of the force of gravity.

Brittleness. Subjected to a stress (more precisely shearing stress), butter should flow without rupture, but in certain cases rupture occurs after the butter has been subjected to a shearing stress. This usually occurs in butters with high solid fat content, i.e., high hardness. Coarse crystal structure and high air content, besides high hardness, may result in extreme brittleness, sometimes called crumbliness.

Setting. This is usually defined as the formation of a crystal structure, or three-dimensional crystal network, following manufacture of the butter (49). After leaving the churn (or the crystallizing chamber, in the case of the continuous process), butter is in an unstable state because the crystallization process is not finished (9). During the first few hours (the length of time being greatly temperature-dependent), crystallization will continue. The formation of structure will carry on during a longer period of time, for a duration of several weeks, but this involves the formation of a three-dimensional crystal network, although crystallization itself is almost completely finished within a period of a few hours after manufacturing.

Recovery. This term is used to describe the ability of butter to regain its structure and consistency after being mechanically worked. Sometimes, the printing of butter is not done immediately after production but after a certain period during which the formation of the structure of butter is completed. In printing machines, butter is subjected to

mechanical working during which a change in consistency occurs. After printing, butter will partially regain its structure.

Thixotropy

Thixotropy is a phenomenon that occurs in coloidal dispersions and is an isothermal reversible sol-gel transformation (6, 22, 35, 36, 62). Thixotropy is defined as a temporary decrease in apparent viscosity during deformation (59). However, not all colloidal dispersions exhibit thixotropy. Two important conditions must be fulfilled before a suspension may show thixotropy. The concentration of the suspended particles must be high enough to permit the formation of a three-dimensional network, and suspended particles must be of irregular shape (needles, rods, plates) (36, 54, 59).

The mechanism of a thixotropic change will be described in some detail because the phenomenon of recovery of structure after mechanical working of butter can be partly explained by thixotropy. It is now accepted that butter is a thixotropic, or plasto-thixotropic substance (67).

According to knowledge at present available, mechanical action applied to a thixotropic suspension will have the following consequences:

(i) The suspended particles are oriented at random and any action that leads to their reorientation will decrease the resistance to flow. This statement is valid only if the size of particles is large enough to prevent an intense Brownian movement, because small particles,

especially at higher temperatures, may have a high kinetic energy and increased Brownian movement tends to annul orientation of particles.

In the case of butter the crystals are large enough (54) that Brownian movement is negligible, and an increase in temperature (as a consequence of transformed mechanical energy of friction) has the opposite effect; a certain amount of crystals will melt, decreasing the concentration of the suspended phase and the viscosity of liquid phase. Both factors cause a decrease in the apparent viscosity of butter.

(ii) During mechanical action, the solid particles in the suspension absorb part of the energy. This absorption is due to the elastic and plastic deformations of the solid particles. As a result of this absorption, the amount of energy left for the orientation of particles is smaller.

Except in some extreme cases of hard waxes, crystals of other fats, including butter, have a low modulus of elasticity, and energy absorption during mechanical working of butter seems to be quite negligible.

(iii) If the mechanical action is intense enough, or the rigidity of solid particles small, disintegration of the particles can occur. The fragments will be more nearly spherical in shape than the original particles and, therefore, the apparent viscosity should decrease.

It seems possible that in some types of so-called butter-homogenizers in which the butter is subjected to a very high shearing

stress, this kind of change takes place. It is unlikely that the original crystals can be reformed from its fragments, and complete recovery of the structure, therefore is not possible.

(iv) A certain amount of liquid phase can be squeezed out of the spaces between crystals; this increases the liquid phase content and therefore decreases the concentration of suspended particles. This will also decrease the apparent viscosity of the suspension.

Something similar will happen when conventionally made butter is subjected to mechanical working. Some of the fat globules, containing both crystalline and liquid fat, will be broken up and crystals and liquid fat will be released. At the usual working temperatures, fat globules contain more liquid than solid phase - which means that by breaking up fat globules, the concentration of suspended particles will decrease. This phenomenon will not occur in the case of continuously made butter because it does not contain fat in globular form.

(v) In some types of suspensions, solid particles may have the shape of long, curled threads, almost without rigidity. The relative movement of adjacent layers during mechanical action will produce a tension and straightening of the particle. This action decreases the number of points of interlocking among particles and finally a decrease of apparent viscosity will occur.

This type of change does not occur with butter (or other fats) because of the shape of the suspended particles.

After mechanical action, a gradual recovery of structure and consistency takes place. However, the recovery will not be complete in all cases. Some of the thixotropic changes, described above, take a long time for recovery, several days, weeks, or months, depending on temperature. In the case of an intense mechanical working, when some of the solid particles are disintegrated, complete recovery is not possible regardless of the length of time or the temperature. Also, when fat globules are broken up, the result is obviously an irreversible process.

Factors influencing consistency of butter

A large number of factors that influence structure and consistency of butter have been described in the literature. A short review of these factors will be presented.

The influence of feed, season, breed, stage of lactation, and climatic conditions on the consistency of butter has been studied extensively (7, 11, 14, 32). Some of these affects can be compensated by adjustment of manufacturing methods, so that more or less uniform products can be obtained.

A great deal of work has been done in investigating the influence of production methods on consistency and structure of butter (4, 14, 15, 21, 30, 31, 46). This involves as main factors thermal and mechanical treatments of cream, churning temperature, temperature of washing water - in the case of conventionally made butter, and similar conditions in the continuous buttermaking process

(7, 10, 39, 40, 72). These studies have shown that manufacturing methods have a great influence on the consistency of butter and that it is quite possible to change the physical properties of butter by adjustment of the production process.

All of the factors that influence the consistency of butter may be divided into two groups, one dealing with chemical, and the other with physical factors. The chemical composition of butter is determined by the first group of factors mentioned earlier, feeding, season, breed and others, and during the manufacturing process nothing can be done to change it. It would be unlawful, according to the present regulations, for instance, to remove a high-melting fat fraction from winter butter in order to obtain a softer product. The only thing that can be done is to adjust the production process to bring about a change in the physical structure of the butter.

Several papers have been published dealing with the influence of air content, degree of dispersion and size of water droplets, size and amount of crystals, type of crystals, arrangement of crystals (often called crystal network), etc. (8, 12, 16, 33, 34, 45, 69). Unfortunately, not all of these factors can be completely controlled and for this reason an unlimited adjustment of the consistency of butter by means of manufacturing methods is not possible.

Working of butter

Two types of mechanical action applied to butter can be distinguished - an unavoidable working during printing of butter,

and an intentional working undertaken to improve the consistency.

When passed through a printing machine, butter is subjected to a mechanical working. In most cases, this leads to a deterioration of consistency. Although the hardness decreases considerably (31), the moisture distribution, which has a great influence on structure, texture, and consistency, becomes worse than before working (39, 51, 52, 70). It was found that the number of small and medium-size droplets decreases, and the number of large droplets increases. The shift in moisture distribution can be so large that free water leaks out of the printing machine. The change in moisture distribution depends, to a great extent, on the rate of shear. It has been shown (50, 70), that at a low rate of shear, the collision of small water droplets will produce larger ones, but at high rate of shear large globules will be broken up into small ones. At all rates of shear, both coalescence of small water droplets and breaking up of large droplets will occur simultaneously. Usually conditions are such that one or the other predominates. However, there are no data in the literature to show what "low" or "high" rates of shear actually mean. It is known that the rate of shear to which butter is subjected by passing through the space occupied by the auger in the printing machine is undoubtedly a low one, because more large water droplets are produced.

The influence of rate of shear on moisture dispersion is less pronounced if the butter is printed immediately after manufacturing because of its lower apparent viscosity which gives a more uniform distribution of the velocity gradient. Also, continuously

made butter is less sensitive to printing because water droplets are much smaller than in the case of churned butter. This means that a larger number of small droplets should be combined to obtain a big one which will appear as free moisture on the surface of the butter.

There is one particular type of printing machine (70) which employs polygonal rollers instead of the usual augers, so that the change in moisture distribution is negligible.

The second type of working is, as was mentioned previously, an intentional working for improving the consistency of butter (73). The hardness of butter is reduced by partial destruction of the three-dimensional crystal network of the solid phase of the butter, this reduction in hardness is sometimes called "work softening" (29). The hardness reduction must be done with such a rate of shear that it will not influence the moisture distribution, i.e. with a high rate of shear.

Several types of machines have been designed and used for working of the butter to improve its consistency after manufacturing. One type is similar to a dough-mixer, where butter is worked under vacuum, which also helps to improve the keeping quality. This type is extensively used in Australia and New Zealand (27). The process of working is used also for adjustment of water and salt content to the required level. The working is divided into two parts. The first part of the working is done at low speed, i.e., with a low rate of shear, to completely break up the blocks of butter. At the end of the first part of the working, the butter has a poor texture, with

lots of free moisture. The second part of the working is done at high speed (high rate of shear), and at the end of this part water is completely incorporated and well dispersed. There are no published data on the changes of hardness or apparent viscosity after working of butter in this so-called vacuum-plasticizing machine. Mention was made only of the improved moisture dispersion and oiling-off property, and also of the improved keeping quality of the butter after working.

Another type of machine for mechanical working of butter is known under the name "Microfix", it is also called a butter homogenizer. There are several papers describing the working of butter with this machine, which is widely used in Europe, although not so extensively on this continent (13, 47, 61).

The main part of the machine is a chamber in which a fast-moving rotor is situated. The working is done with a high rate of shear. While the action of the vacuum-plasticizer is a discontinuous one, the Microfix is a machine with continuous action, and it can be connected directly to a printing machine.

Hardness decreases considerably after working (2 - 3 times) and microscopic examination showed that moisture distribution and milk solids (protein) dispersion were satisfactory (47). There are some difficulties when handling hard butter (at -4°C) and it has been suggested that blocks of such hard butter should be cut into smaller pieces before introduction into the Microfix.

The two types of machines described are used for mechanical working of butter several days, weeks, or even months, after manufacturing. During storage of the butter, setting is virtually complete and the influence of working on hardness and apparent viscosity of such "stabilized" butter will be relatively great.

Another method for mechanical working of butter is applied in continuous buttermaking, the machine used being an integral part of the manufacturing equipment. When the butter leaves the crystallizing chamber of a continuous buttermaking machine, the crystallization process is still far from completion. Crystallization of milk fat is a relatively slow process and it can be accelerated only to a limited extent (40). Dilatometric investigations of milk fat crystallization show that under conditions of rapid cooling, crystallization is complete after three hours, whereas with slow cooling crystallization takes over twenty-four hours (17, 18). Although heat transfer in the crystallizing chamber is higher than in the dilatometric experiments, due to the intense agitation of the butter, the time necessary for complete crystal formation is much longer than the holding time in the crystallizing chamber. This means that the crystallization process will continue outside the chamber because the crystals and the supercooled liquid fat are not in thermal equilibrium.

To prolong the time available for crystallization, a special device, the texturator, has been added to the continuous buttermaking machine. Several types of texturators have been

described (39, 40, 74, 75) in which the butter is subjected to shearing stresses, but generally with a low rate of shear. Although there is some improvement in consistency (the setting is not so pronounced), this kind of treatment is insufficient to decrease the setting to such an extent that its influence on consistency becomes negligible.

To improve the consistency of continuously made butter, two conditions must be fulfilled, first, the time interval between the exit of the butter from the crystallizing chamber and the beginning of working should be sufficient to allow an almost complete crystallization, and second, the working should be done at a high rate of shear, e.g. by means of a fast-moving rotor or possibly by forcing the butter at high speed through a screen, instead of pushing it through a perforated plate as is done at the present time.

The proposed modification of the continuous production process would possibly yield butter with a lower hardness and less pronounced setting, and therefore, with a better consistency.

Recovery of consistency after working

During the storage of worked butter a complex physical change occurs. Thixotropy is undoubtedly responsible for part of the structural recovery, as was mentioned previously. However, the change of structure during mechanical working is not always completely reversible.

Mechanical working of butter is always accompanied with a certain evolution of heat which leads to a partial melting of the crystals. During the recovery period this amount of melted fat will crystallize again, but under quite different conditions than those which prevailed during the initial crystallization when the butter was produced. A different type of crystals with different physical properties will be formed, and this could have an influence on the consistency of the butter.

A partial destruction of the large crystals might be the cause of the irreversible decrease in hardness. This could be due to the fact that a recovery of the original crystals from their fragments is extremely difficult, because the mobility of crystal fragments is low at the high viscosity prevailing in the suspension.

Several papers have been published in which it was stated that the initial structure of the butter is not restored after mechanical working (6, 15, 20, 57). It has been shown also that under certain extreme conditions the recovery of structure is almost complete (67, 68).

It can be stated that under normal conditions the recovery of structure of butter, after mechanical working, will be incomplete as a result of irreversible changes in the butter during working.

Instruments for the measurement of physical properties of plastic fats

Many instruments are in use for the measurement of physical properties of plastic fats. It is beyond the scope of this work to give a detailed description of all of these and therefore only a short summary will be given. The instruments can be divided into several groups, each group using one physical principle for the determination of some properties of the material.

Flow through a (capillary) tube. There are many variants of this general principle but all of these have one thing in common, they all measure the dependance of the transported volume of the material per unit time on the pressure differential necessary to produce the flow. The methods vary from each other in having different velocity distributions along the radius of the tube (1, 53).

Extrusion or flow through an orifice. This method uses the well known hydrodynamic property of fluids, i.e. that the resistance of flow increases considerably if there is a sudden contraction in the duct. Two main subdivisions might be made, in one group the experiments are carried out at a constant speed of extrusion and variation of extrusion pressure is recorded (35, 58), and in the other group the extrusion is done under a constant load and the change of speed or flow is measured (56).

Falling weight. The viscous drag, i.e. the property of a substance by which it resists the motion of a solid body through

it is used in this case. The Stokes falling-sphere formula for Newtonian fluids was derived by using this principle. For non-Newtonian fluids a falling cylinder can be used, and the speed of movement under a constant load is measured (53).

Rotation of spindle or cylinder. This is a modification of the previous method. Instead of using a linear motion rotation is used, which enables a prolonged measurement, and by a continuous variation of speed the occurrence of thixotropy can be detected. A variety of instruments has been designed (35, 53), differing from one another in construction details only.

Damping of vibrations. A magnetostrictive sensitive element which has longitudinal vibrations is the main part of this type of instrument. The intensity of the signal generated by the vibration depends on the damping properties of the tested substance, which, in turn, is a function of the consistency (35).

The five methods mentioned are used primarily for the determination of apparent viscosity, although some (flow through capillary tube, extrusion and rotation of spindle) may be useful for the determination of yield value. The results of the measurements are often expressed in arbitrary units and this presents difficulty in the comparison of different methods.

Penetration into test material. The resistance to penetration of a solid body into the test substance has been used to measure its consistency, or more correctly, one property influencing the consistency. A ball, needle, cone, or disc can be used and the

depth of penetration, or area of impression, is measured. A variety of instruments of this type has been described (23, 26, 28, 37, 41, 48).

Sectility method. Resistance to cutting is measured using a taut wire, and the force required to push the wire through the material at a constant speed is measured (41, 42, 44, 46).

With the penetration method the hardness of a plastic substance can be determined. As the experimental conditions are different when different instruments are used, even if the results are expressed in absolute units, the numerical values may differ considerably. There is little published information on the correlation of measurements obtained with different instruments.

It has been stated in some cases that hardness can be measured by the sectility method, because a direct correlation between the penetration and sectility methods was found. It seems likely, however, that the properties which can be evaluated by these are different in principle, the penetration method is a static one, whereas the sectility method is dynamic.

Compression test. This type of examination of consistency is used to measure yield value, resistance to deformation, and apparent viscosity. The speed of compression of the substance under a constant load is determined (63, 65).

Spreadability test. Specially designed devices, intended to simulate conditions of spreading butter on a piece of bread, are used in this type of test (43, 60, 65). It is not likely that this method could give useful results because the spreading capacity of butter is a complex property consisting primarily of hardness, apparent viscosity, and the magnitude of the yield value. It would probably be better to use the available research capacities for investigations of more basic properties.

EXPERIMENTAL METHODS

Source of samples

Butter for the experimental part of this work was obtained from the Northern Alberta Dairy Pool Ltd., in Edmonton. Two types of butter were used in the experiments, conventional (churned) and continuously made butter, both were produced at the end of May, 1964.

The butter was stored for one month in the freezer at -20°C, followed by another month at 5°C, before the experiments were made. Both butters were of normal composition, i.e. with about 81% milk fat, 16% water, 2% salt, and 1% milk solids. The moisture was well incorporated but after the boxes were opened, it was noticed that the surface of the butter had a slightly deeper colour, probably due to some loss of moisture. These surface layers were discarded before the experiments.

Instruments used in the experimental procedure

(i) Modified meat grinding machine. Mechanical working of the butter was carried out by means of a small electric meat grinding machine, Philips Model KB 5300 (Figs. 1 and 2). The four-blade knife and the original perforated plate were removed and replaced by an attachment with a cross-section as shown in Fig. 3. The attachment consisted of a short cylinder 6 in which a perforated plate 5 could be fixed by means of spacer rings 7. The end cone 8

was used for sampling. Three different perforated plates were used in the experiments, the first plate with one large hole of 2.064 cm (13/16 in.) in diameter, a second plate with 19 holes which each had a diameter of 0.476 cm (3/16 in.) and a third plate with 41 holes of 0.318 cm (1/8 in.) in diameter each. The total area of the holes in each case was approximately 3.38 cm^2 (0.521 sq. in.).

The inner diameter of the spacer rings was 3.81 cm (1 1/2 in.) with an area of 11.40 cm^2 (1.767 sq. in.).

The conical part for sampling was designed so that it fitted the extrusion die (a piece of stainless steel tubing of 1 in. outside diameter).

(ii) Cone penetrometer. A cone penetrometer (Fig. 4) was used for measurements of the hardness of the butter before and after working, as well as before and after extrusion. The penetrometer met A.S.T.M. Designations D 5, D 217, and D 937, and also A.O.C.S. Tentative Method Cc 16-60, and was made by Precision Scientific Co., Chicago.

The cone itself had a total central angle of 20°, while the total weight of the cone assembly and the shaft was 92.5 g. The smallest division on the dial of the reading instrument was one-tenth of a millimeter.

(iii) Shear press. For extrusion of the butter, the Lee-Kramer shear press, Model SP-12, with an electronic recording attachment, was used (Fig. 5).

The shear press is, in fact, a multi-purpose instrument for evaluation of different rheological and mechanical properties of foodstuffs. In this particular case it was adapted for extrusion of butter.

A block diagram of the shear press is given in Fig. 6. The basic unit consists of a hydraulic drive system 1 and 2, for moving a piston which is attached to a piston rod. The speed of the piston is continuously adjustable from 0 to 30 cm/min (12 in./min). The control system of the press consists of the pressure control valve 6, the speed control valve 5, the directional valve 3, and the hydraulic pressure indicator 7. On the other side of the piston rod is the detection element, the so-called proving ring 9. The proving ring is a precisely machined steel ring fitted with an electric transducer element. Under the influence of the external force which appears as a result of resistance of the sample to deformation, the proving ring is deformed, i.e. compressed. The deformation of the ring is transformed by means of the transducer into an electric signal which is then amplified and fed into the recorder to obtain a force - stroke curve.

The proving ring used in the experiments had a load range of 0 to 500 lbs. and the sensitivity of the electronic recording attachment was selected to 50 lbs. for full-scale deflection.

The extrusion attachment consisted of a brass plunger 10 attached to the proving ring to enable the measurement of the variation in the extrusion force. The plunger was provided with an O-ring at

the lower end. The extrusion dies 11 were constructed from sections of 1 in. stainless steel tubing, 3 1/4 in. long. The bottom plate had a sharp-edged orifice of 4 mm. diameter, and was fixed to the tube by means of a union ferrule and nut.

The extrusion plunger and the disassembled extrusion die are shown in Fig. 7.

(iv) Thermometer. All temperature measurements were made with a YSI Tele-Thermometer, Model 42. The temperatures of the samples were measured before and after working and also before and after extrusion. The Tele-Thermometer was used instead of an ordinary mercury thermometer because it has a smaller thermal capacity and, therefore, a smaller thermal inertia which cuts the time of the temperature equalization.

Working of butter

Mechanical working of the butter was carried out at 5°C in a temperature-controlled room.

The working of butter in this case occurs actually at two places. One part of the working is done during helical flow of the butter through the grooves of the auger, and another part during passage of the butter through the perforated plate of the working attachment.

Four sample series were prepared. The first series was a control and contained the unworked butter, while the second, third,

and fourth series were obtained by working of the butter through the plates with one, nineteen, and forty-one holes, respectively.

In this type of experiment it was not possible to determine the exact amount of work put into the butter, but a comparison of the velocities was made, because it could be supposed that the work done is proportional to the velocity of flow.

The machine was fed manually and therefore the flow of butter was not absolutely constant. The rate of flow varied from 80 to 120 g/min. with an average value of $Q = 100$ g/min. Assuming an average value of 0.94 g/cm^3 for the specific gravity of butter, the velocity of flow can be calculated using the continuity equation:

$$v = \frac{Q}{A \times \gamma} = \frac{100}{A \times 0.94} = \frac{106.5}{A} \text{ cm/min} \quad . \; . \; . \; . \; . \; (1)$$

where A represents the area of the cross-section expressed in cm^2.

Three characteristic cross-sections were selected, i.e. the helical groove of the auger, spacer rings, and the total area of holes in the perforated plate and they were 2.20 cm^2, 11.40 cm^2, and 3.38 cm^2 with corresponding speeds, calculated from the equation (1) of 48.4 cm/min., 9.34 cm/min., and 31.5 cm/min., respectively. These velocities can be used as qualitative indicators of the rate of shear and they can be used for such purpose regardless of the velocity distribution along the radius of the cross section.

In the simplest case of velocity distribution (Bingham's fluid) when butter is assumed to flow with constant apparent

viscosity after a definite magnitude of shearing stress has been achieved (yield value), there is an external region near the walls in which a velocity gradient exists, while the interior portion of the butter flows with a uniform velocity as a solid plug. The ratio between the shearing stress and the rate of shear remains constant in this particular case which means that an increase in velocity will induce a higher rate of shear and also a higher shearing stress. Shearing stress, on the other hand, depends on the applied pressure which induces the flow or on the work done per unit volume of the flowing substance.

Even more complex (and more correct) representations of velocity distribution in the cross-section of the tube, such as the power function of the rate of shear or the hyperbolic sine speed law, lead to similar conclusions, although in this case the apparent viscosity is not constant but depends in some way on the rate of shear.

The numerical values for velocities of flow through the different sections of the machine used for working show that the highest velocity was obtained in the grooves of the auger (48.4 cm/min.), then through the perforated plate (31.5 cm/min.), and the lowest through the spacer rings (9.34 cm/min.). Because of the fact that the work done is proportional to the velocity as it was derived above, it can be concluded that approximately 54% of the total work is received by the butter during the flow through the grooves of the auger, 35% during the flow through the perforated plate, and 11% during the flow through the spacer rings.

During the working of butter, the moisture distribution was slightly changed, approximately 12% of the total moisture present in the butter was expelled. This undoubtedly indicates that the rate of shear was low so that a certain amount of large water droplets was formed which ran off as free moisture from the machine. The liberation of water was observed in the space occupied by the auger and this means that even the rate of shear induced by the velocity of flow of 48.4 cm/min. was insufficient. This indicates that the working, or at least its final part, should be done at higher rates of shear, if one desires to avoid the formation of free moisture.

A certain amount of heat was evolved during mechanical working as a result of the friction between adjacent layers of butter due to the existence of a velocity gradient. The heat produced by friction caused an increase in temperature of the butter of approximately 1.5 - 2.5^{o}C.

Penetration measurements

For measurements of penetration values, samples were filled in cylindrical stainless steel rings of 2 in. outside diameter and 1 1/4 in. high. Four replicates of each sample series were prepared. The upper surface of the butter was smoothed carefully by cutting out the butter above the frame by means of a taut wire to obtain a smooth plane surface necessary for the penetration tests.

The samples were left 24 hrs. after filling to obtain complete temperature equalization. To avoid loss of moisture from

the surface layers the samples were covered with aluminum foil.

The penetration values were obtained at two different temperatures, 5° and $15^{\circ}C$. In both cases the time of penetration of the cone was 10 sec. Five readings were made on each sample and the mean value was calculated. The temperature of the samples was not always exactly $5^{\circ}C$ and therefore a temperature correction was made. The penetration values were corrected by 0.9 penetration units per 0.1 degree centigrade difference from $5^{\circ}C$ (55). The mean penetration value was calculated after correction of the whole sample series (three samples) and then converted into hardness units.

The conversion of penetration values into hardness units was done according to the previously proposed definition of hardness, i.e. the total weight of the cone assembly and the shaft (92.5 g) was divided by the area of impression.

The conversion equation is of the following form:

$$H_p = \frac{G}{A} = \frac{G \times 10^{-3}}{\left[h\pi \frac{\operatorname{tg}\alpha}{\cos\alpha} \left(h + \frac{2r}{\operatorname{tg}\alpha} \right) + r^2\pi \right] 10^{-4}} \qquad (2)$$

where,

H_p = hardness value in kg/cm^2

G = total weight of the cone assembly in g.

A = area of impression, in cm^2

h = depth of penetration of the cone in 1/10 mm.

α = half-angle of the cone

r = radius of the flat surface of the cone tip in 1/10 mm.

Equation (2) was derived using Fig. 8.

By means of equation (2), hardness values were calculated for different penetration values and they are listed in Tab. 1 and are also given in Fig. 9.

Penetration values were measured at 5°C on one, eight and fifteen days after the experiments to obtain information on the setting of the butter.

One replicate of each sample series was held at 15°C for three days after preparation, and then the penetration values were measured at the same temperature.

To obtain information on the influence of extrusion on the hardness of butter, the extruded butter was filled into frames after extrusion, and penetration values measured at 15°C one day after filling.

Extrusion measurements

This part of the experimental work was done at 15°C in a temperature-controlled room. The speed of the extrusion plunger was maintained constant throughout the experiments and was 10 cm/min. (4 in./min.). The extrusion dies were filled immediately after working, transferred from 5° to 15°C, and left three days before extrusion to obtain complete temperature equalization. The temperature of the samples before extrusion was 15° ± 0.5°C.

The extrusion ratio, i.e. the ratio between the cross-section of unextruded and extruded sample was:

$$r = \frac{A_o}{A_1} = \frac{d_o^2}{d_1^2} = \frac{23^2}{4^2} = 33$$

where,

d_o = 23 mm, inner diameter of the extrusion die

d_1 = 4 mm, diameter of the orifice in the bottom plate.

The speed of extrusion was:

$$v = v_p \times r = 10 \times 33 = 330 \text{ cm/min}$$

where,

v_p = 10 cm/min, the speed of the extrusion plunger.

The percentage reduction of area was:

$$\rho = \frac{A_o - A_1}{A_o} \times 100 = \frac{d_o^2 - d_1^2}{d_o^2} \times 100 = \frac{23^2 - 4^2}{4^2} \times 100 = 96.8\%$$

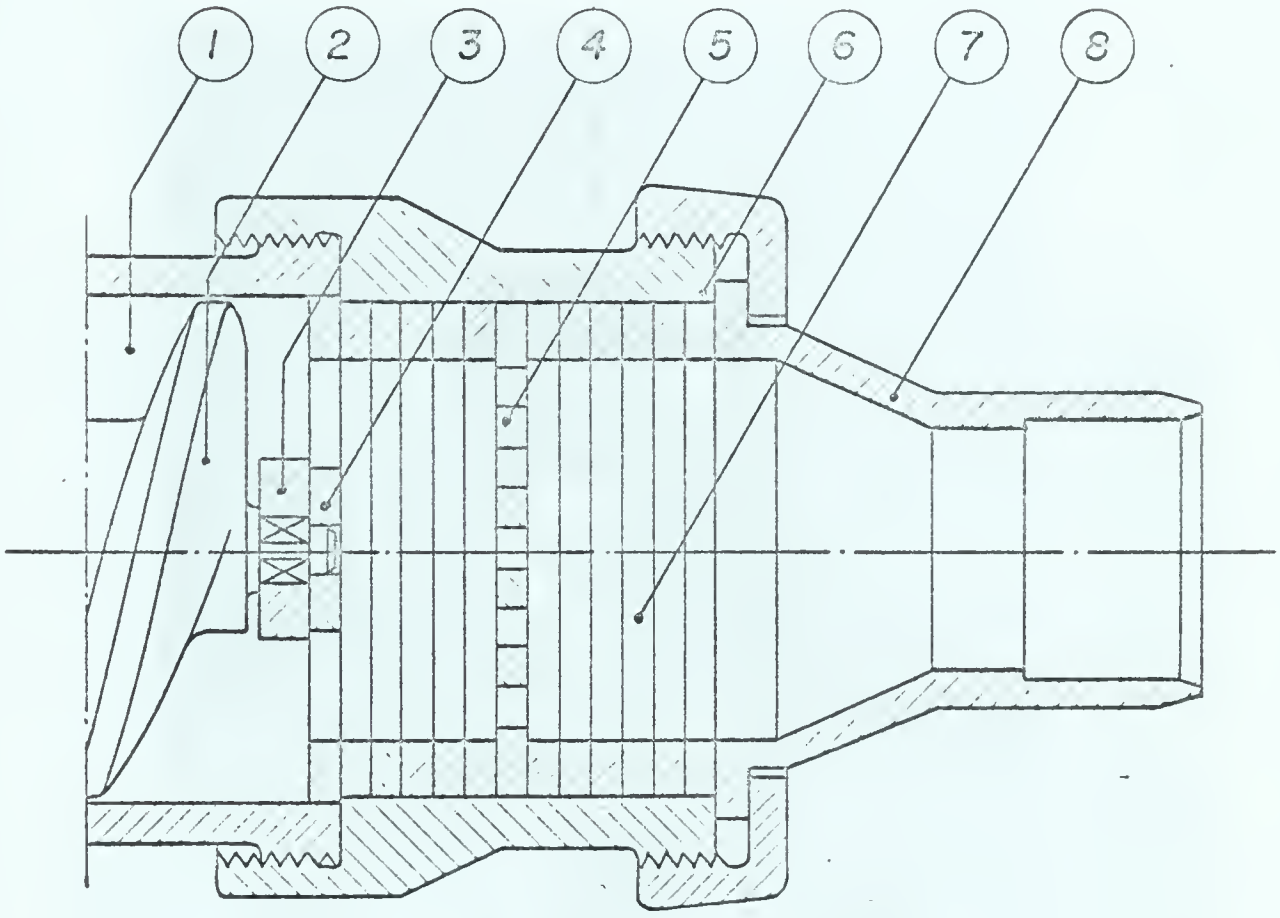
Five replicate samples of each series were prepared, three of them were extruded, while the other two were used for the determination of the coefficient of friction between the extrusion die and the plunger and butter. The weight of butter was measured after extrusion and all results were expressed on the basis of one gram of butter.

There was no noticeable change in temperature after extrusion which indicated that the extrusion was done under isothermal conditions.

The moisture distribution remained unchanged because no leaking of free moisture was observed.

Fig. 1. Modified meat grinding machine for mechanical working of butter

Fig. 2. Meat grinding machine for mechanical working of butter - disassembled



1 - Body of the meat grinding machine

2 - The auger

3 - Spacer ring

4 - Support for the auger

5 - Perforated plate

6 - Cylinder

7 - Spacer ring

8 - End cone for sampling

Fig. 3. The cross-section through the attachment for mechanical working of butter

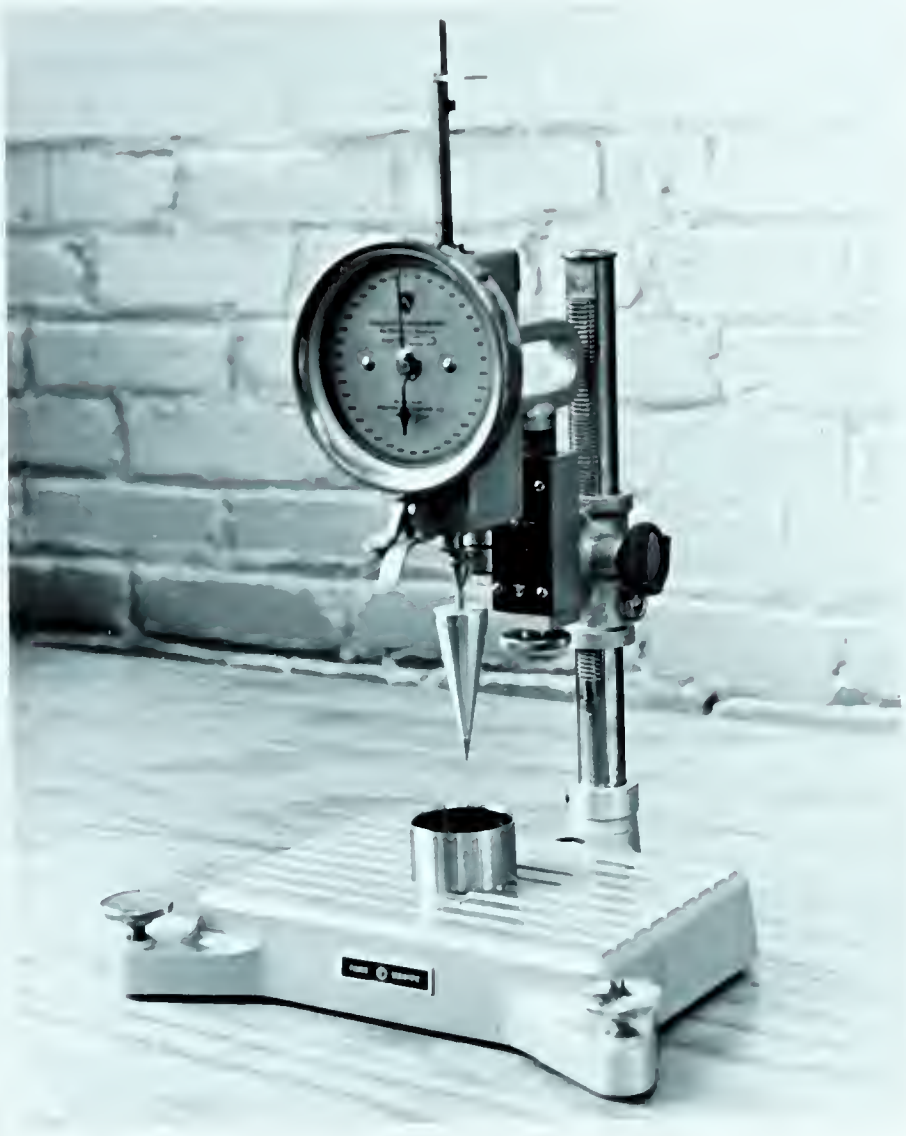


Fig. 4. Cone penetrometer

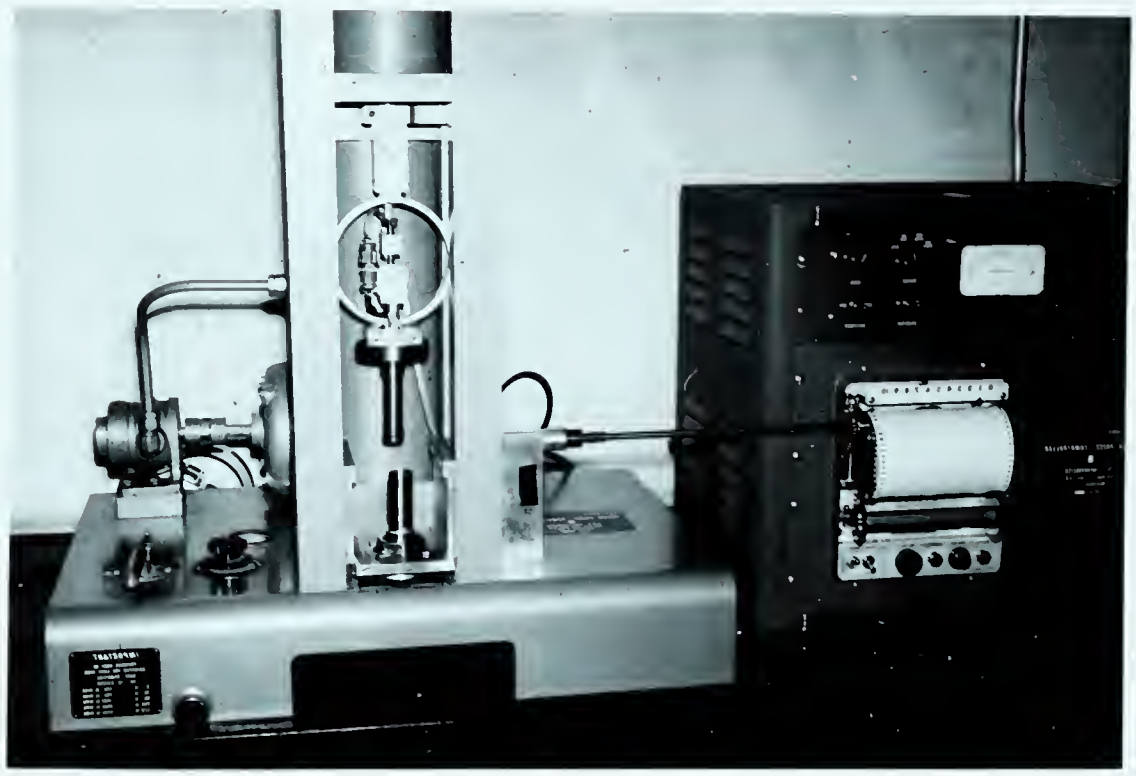
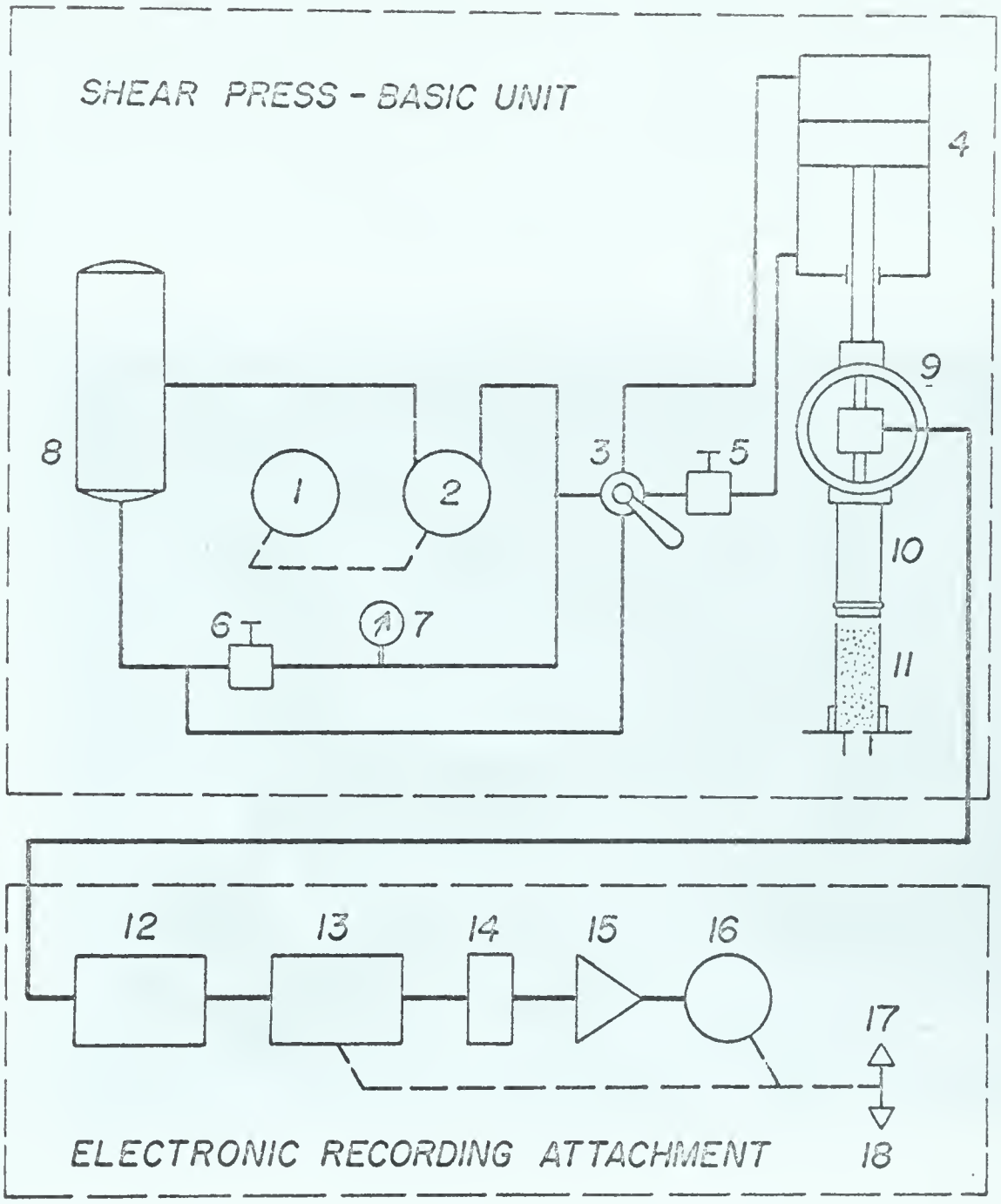


Fig. 5. Shear press



1 - ELECTRIC MOTOR
2 - GEAR PUMP
3 - DIRECTIONAL VALVE
4 - CYLINDER
5 - SPEED CONTROL VALVE
6 - PRESSURE CONTROL VALVE
7 - HYDRAULIC PRESSURE INDICATOR
8 - RECEIVER
9 - PROVING RING
10 - EXTRUSION PLUNGER
11 - EXTRUSION DIE
12 - PRE-AMPLIFIER
13 - MEASURING CIRCUIT
14 - CHOPPER
15 - SERVO-AMPLIFIER
16 - BALANCING MOTOR
17 - INDICATING POINTER
18 - RECORDING PEN

Fig. 6. Block diagram of the shear press

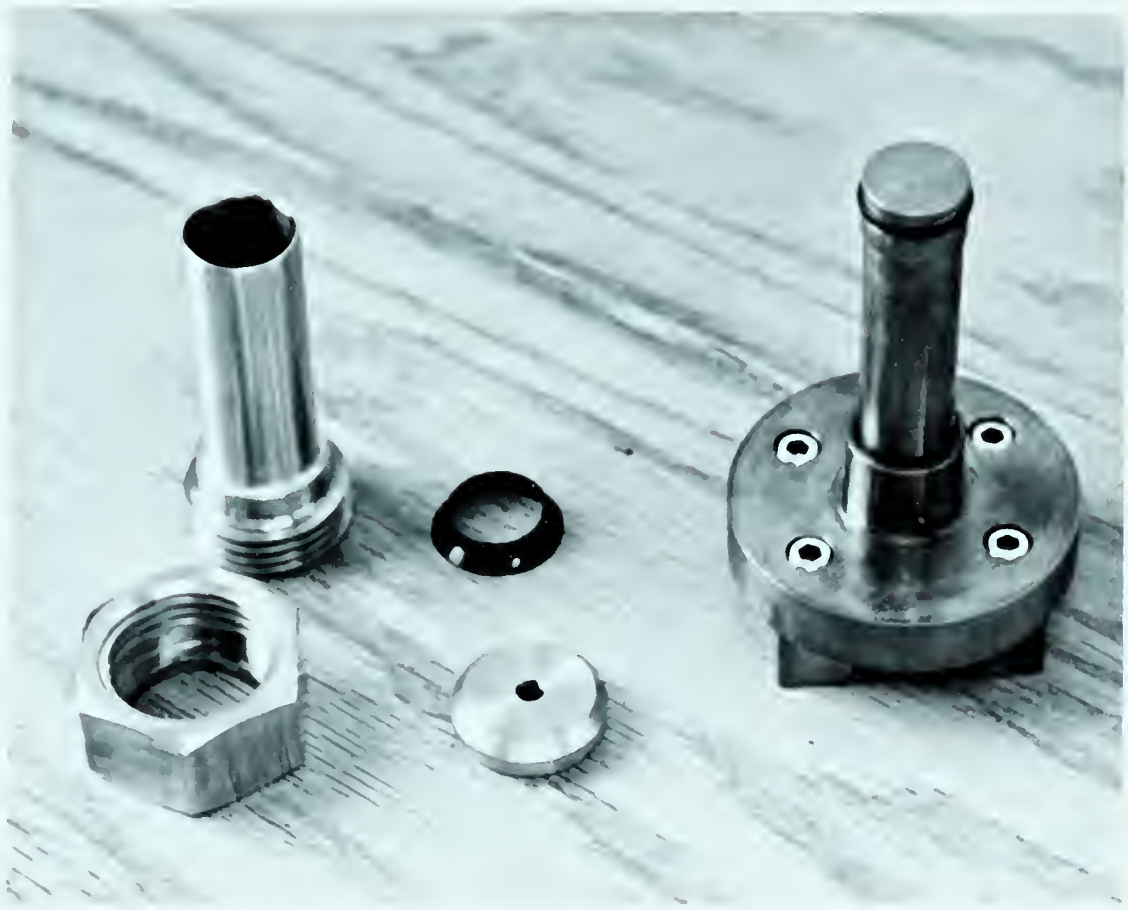


Fig. 7. The extrusion die and plunger

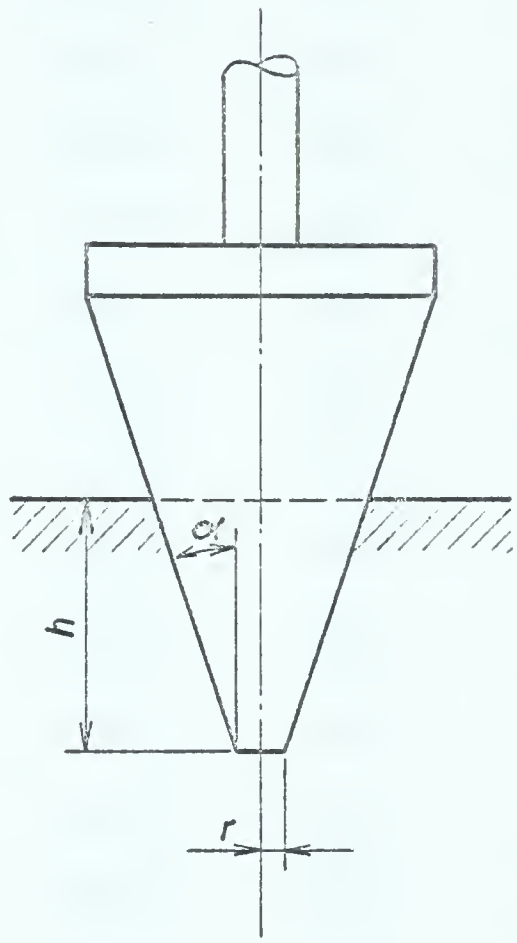


Fig. 8. Calculation the area of the impression of the cone

Table 1. Conversion table for the determination of hardness from penetration values

h	H_p	h	H_p
5	4.865	105	0.104
10	2.577	110	0.096
15	1.664	115	0.089
20	1.185	120	0.083
25	0.895	125	0.077
30	0.703	130	0.072
35	0.569	135	0.067
40	0.471	140	0.063
45	0.397	145	0.059
50	0.340	150	0.056
55	0.294	155	0.053
60	0.257	160	0.050
65	0.227	165	0.047
70	0.202	170	0.045
75	0.181	175	0.043
80	0.163	180	0.041
85	0.148	185	0.039
90	0.134	190	0.037
95	0.123	195	0.035
100	0.113	200	0.033

h - Penetration values obtained by cone penetrometer at $5^{o}C$, in 1/10 mm, 10 sec.

H_p - Hardness, in kg/cm^2

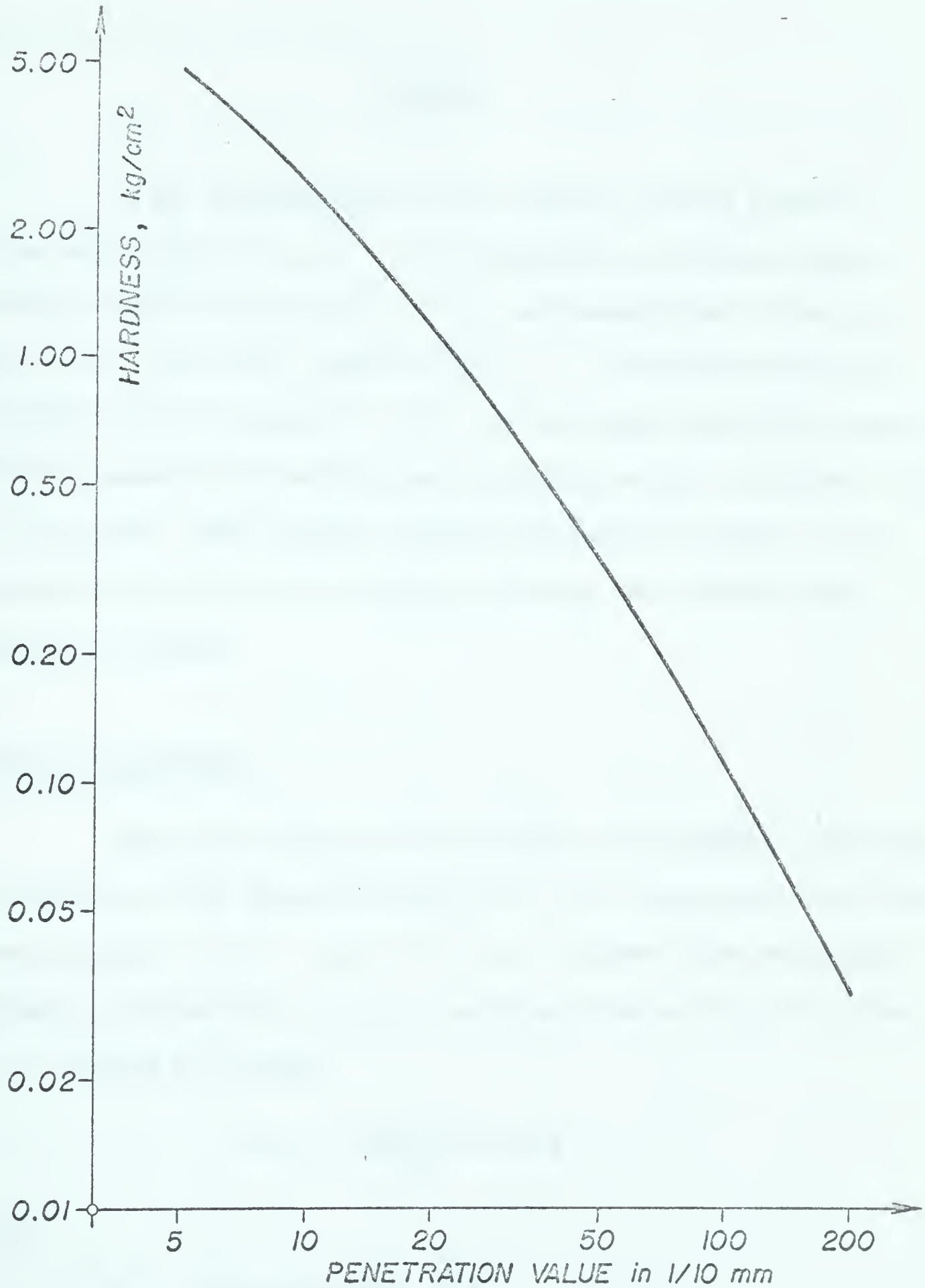


Fig. 9. Conversion diagram for the determination of hardness from penetration values

RESULTS

In the interpretation of the results, several abbreviations and symbols are used. In all diagrams conventionally made (churned) butter is denoted by "A" and continuously made butter is marked "B". The control sample series, i.e. the sample series of unworked butter is denoted by "00", and the sample series of butters worked by means of the modified meat grinding machine are marked "01", "19", and "43", these figures indicate the number of holes of the perforated plate (Fig. 3) through which butter was forced during mechanical working.

Working and hardness

Mechanical treatment of butter had a considerable influence on hardness and the results of this part of the experimental work are shown in Tables 2 and 3, and in Fig. 11. The term "work softening" is used to express the decrease in hardness after mechanical working and is defined as follows:

$$WS = \frac{H_o - H_w}{H_o} \times 100\ \%$$

where,

WS = work softening, in %

H_o = hardness of unworked butter (control sample series 00), in kg/cm^2

H_w = hardness of worked butter, in kg/cm^2

Recovery of consistency after working

Under favourable conditions, worked butter will gradually regain its original structure although the original state will not be recovered completely. In Table 4, and Figs. 12 and 13, the results of hardness recovery are given. The temperature during the recovery period was 5°C, the same as the temperature of working, so that no recrystallization could take place. The "residual hardness" is expressed as the hardness of a particular sample in relation to the hardness of the control sample series, i.e.,

$$RH = \frac{H_w}{H_o} \times 100\ \%$$

where,

RH = residual hardness after mechanical working, in %

H_w = hardness of worked butter, in kg/cm^2

H_o = hardness of control sample series (unworked butter), in kg/cm^2.

Extrusion and hardness

Extrusion of butter also had a certain influence on consistency, although this influence was not as pronounced as in the case of mechanical working. The change in hardness of butter and the "extrusion softening", i.e. the decrease of hardness due to the extrusion is shown in Table 5 and Fig. 14. This part of the experimental work was carried out at a temperature of 15°C.

The influence of the initial hardness on the extrusion pressure, and the specific work of the extrusion, are given in Table 6

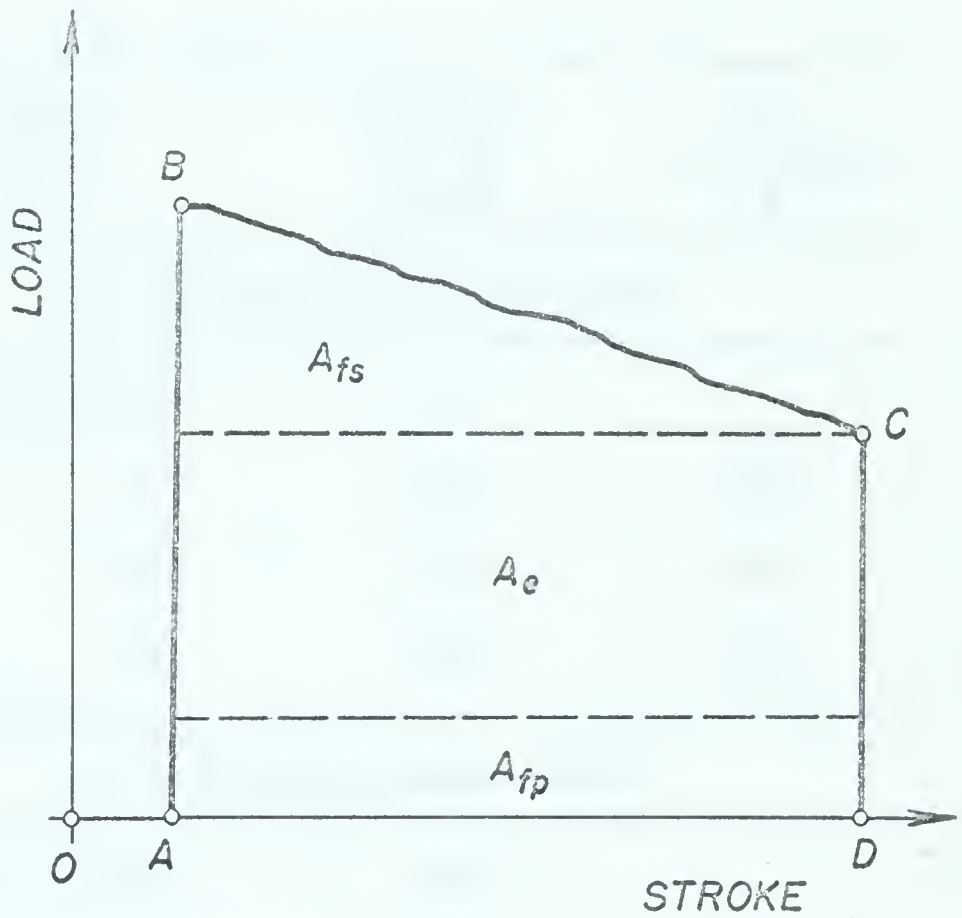
and Figs. 15 and 16. The extrusion pressure was calculated as the ratio of the average force during the extrusion which was taken from the extrusion diagram and the cross-section area of the extrusion die which was 4.15 cm^2. The specific work of extrusion was calculated as follows:

$$W = \frac{1}{G}\left[A_t - (A_{fs} + A_{fp})\right] \times c \quad \text{kg cm/g}$$

where,

W	=	specific work of extrusion, in kg cm/g
G	=	weight of the extruded sample, in g
A_t	=	total area of the extrusion diagram, in cm^2
A_{fs}, A_{fp}	=	area corresponding to the friction of sample and plunger respectively, in cm^2
c	=	conversion factor which represents the ratio of readings and actual values of force and stroke of extrusion plunger - in this case 2.21 kg cm/cm^2.

The "residual specific work" is also given in Table 6 and Fig. 15. The change in the magnitude of the specific work of the extrusion is due to the previous mechanical working. The residual specific work of extrusion is defined in the same manner as the residual hardness, i.e. it is expressed as the specific work of the extrusion for each particular sample series, taking the specific work of extrusion of the control sample series as 100%.



A_e – Area of extrusion

A_{fs} – Area of friction of sample

A_{fp} – Area of friction of extrusion plunger

Fig. 10. A typical extrusion diagram of butter

Table 2. Relationship between mechanical working and hardness at 5°C

Sample series	Hardness at 5°C kg/cm^2	Work softening %
A. Conventionally made butter		
Control (00)	0.411	-
01	0.212	48.4
19	0.207	49.6
43	0.202	50.9
B. Continuously made butter		
Control (00)	0.895	-
01	0.271	69.7
19	0.264	70.5
43	0.257	71.3

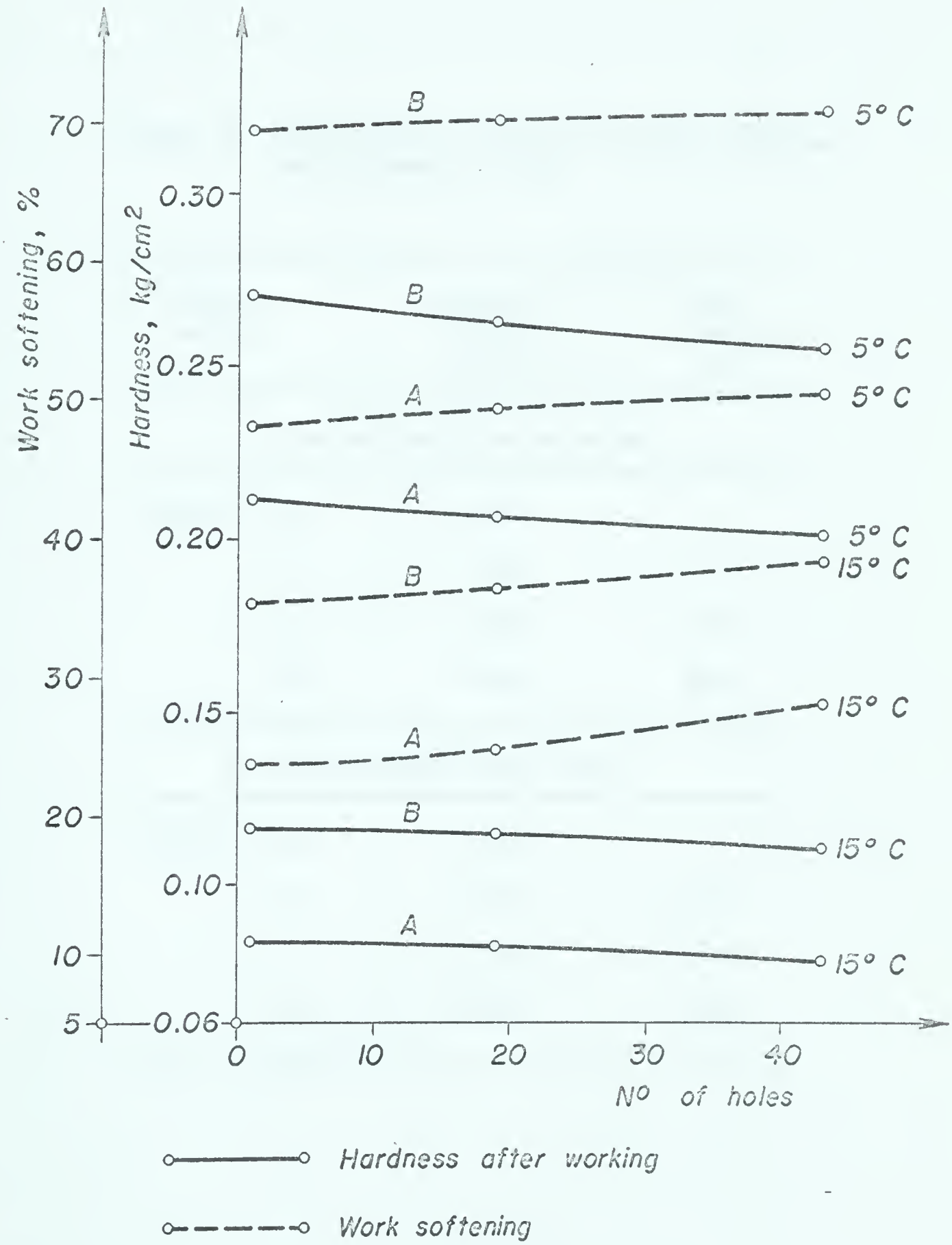


Fig. 11. Relationship between mechanical working and hardness at 5° and 15°C

Table 3. Relationship between mechanical working and hardness at 15°C

Sample series	Hardness at 15°C kg/cm²	Work softening %
A. Conventionally made butter		
Control (00)	0.109	-
01	0.083	23.8
19	0.082	24.8
43	0.078	28.4
B. Continuously made butter		
Control (00)	0.181	-
01	0.117	35.4
19	0.115	36.5
43	0.111	38.7

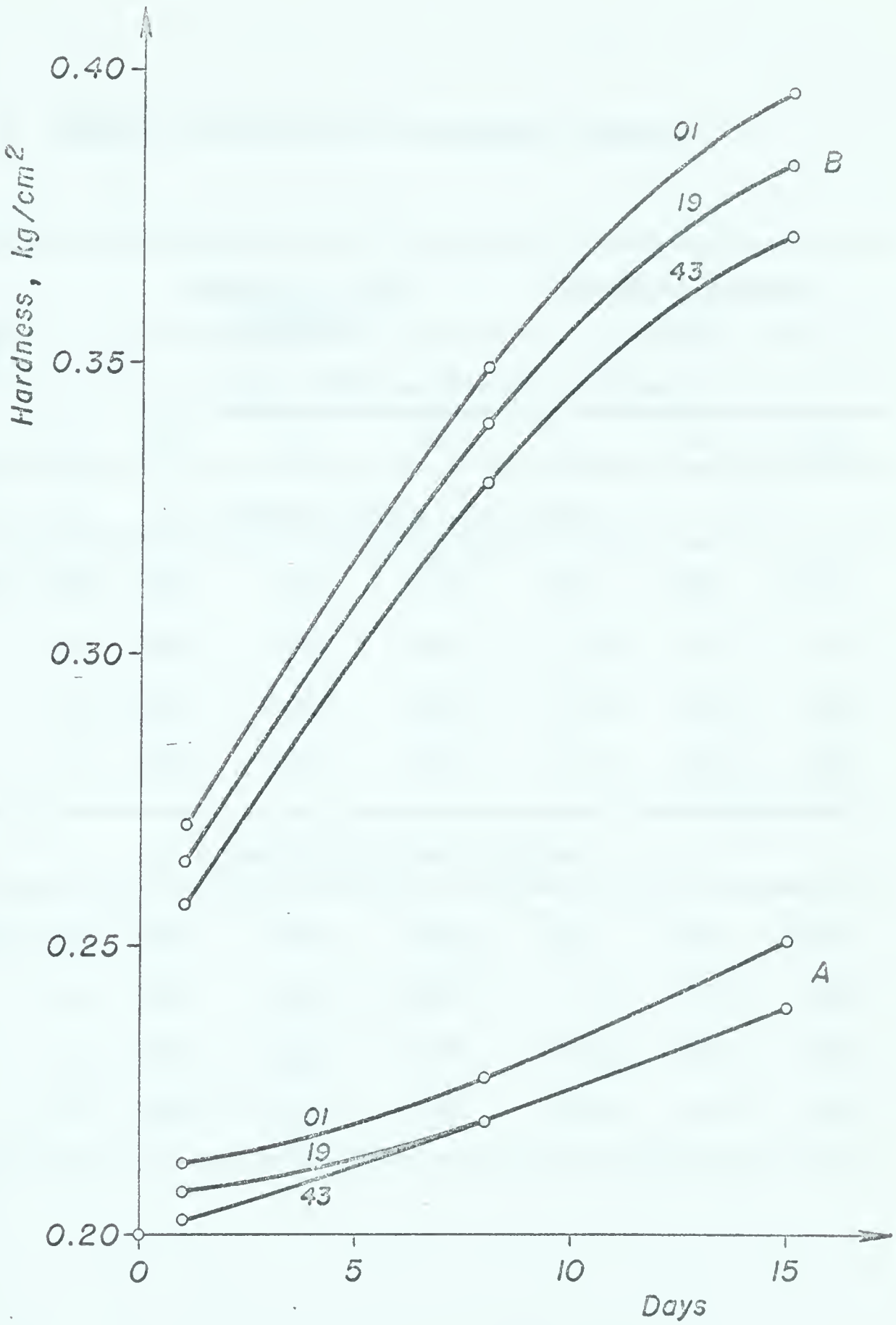


Fig. 12. Hardness recovery after mechanical working

Table 4. Hardness recovery after mechanical working

Sample series	Hardness at 5°C kg/cm²			Residual hardness %		
	Days after mechanical treatment					
	1	8	15	1	8	15
A. Conventionally made butter						
Control (00)	0.411	0.425	0.439	100	100	100
01	0.212	0.227	0.251	51.6	53.4	57.2
19	0.207	0.222	0.239	50.4	52.2	54.5
43	0.202	0.222	0.239	49.2	52.2	54.5
B. Continuously made butter						
Control (00)	0.895	0.995	0.995	100	100	100
01	0.271	0.350	0.397	30.3	35.2	39.9
19	0.264	0.340	0.385	29.5	34.2	38.7
43	0.257	0.330	0.373	28.7	33.2	37.5

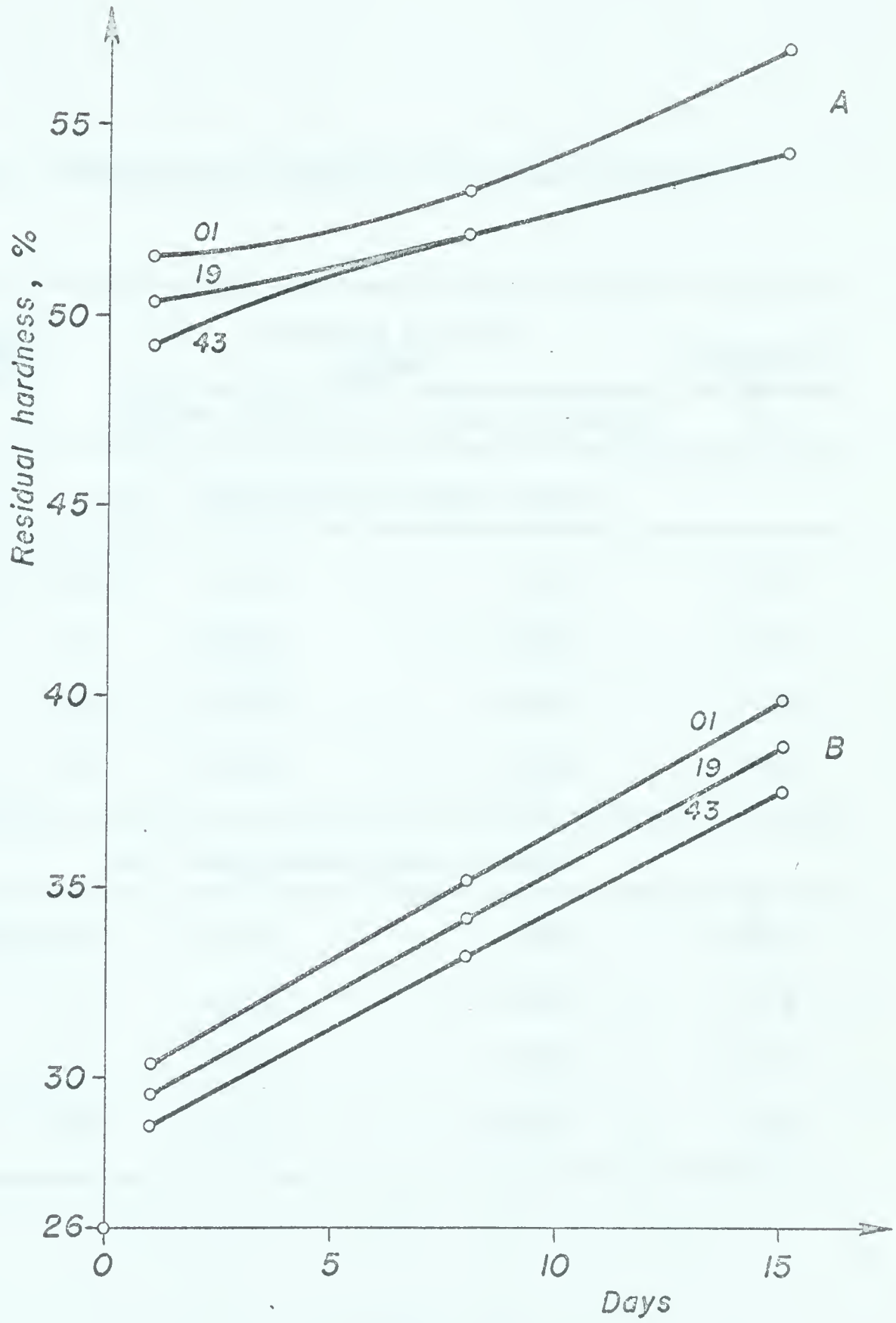


Fig. 13. Residual hardness after mechanical working

Table 5. Hardness and extrusion softening of butter

Sample series	Hardness at 15°C kg/cm²		Extrusion softening %
	before extrusion	after extrusion	
A. Conventionally made butter			
Control (00)	0.109	0.083	23.9
01	0.083	0.073	12.0
19	0.082	0.071	13.4
43	0.078	0.070	10.3
B. Continuously made butter			
Control (00)	0.181	0.076	58.0
01	0.117	0.071	39.3
19	0.115	0.069	40.0
43	0.111	0.066	40.5

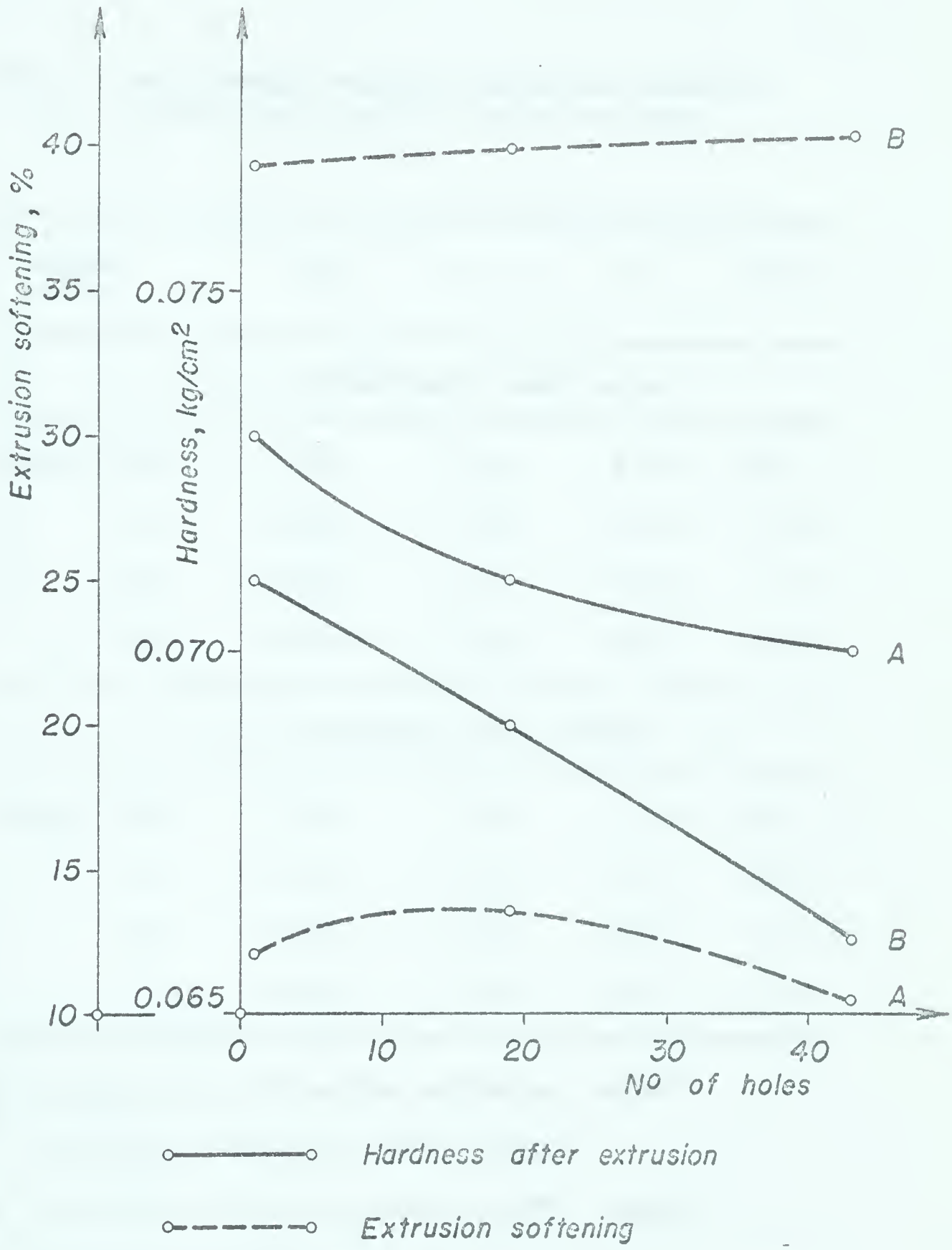


Fig. 14. Hardness and extrusion softening of butter

Table 6. Relationship between hardness and extrusion pressure and specific work of extrusion

Sample series	H_p	p	W	RW
A. Conventionally made butter				
Control (00)	0.109	1.13	1.23	100
01	0.083	0.85	0.92	74.8
19	0.082	0.83	0.90	73.2
43	0.078	0.79	0.86	70.0
B. Continuously made butter				
Control (00)	0.181	1.49	1.55	100
01	0.117	0.92	0.96	61.9
19	0.115	0.88	0.92	59.3
43	0.111	0.84	0.87	56.1

H_p - Hardness at 15°C before extrusion, kg/cm^2

p - Extrusion pressure at 15°C, kg/cm^2

W - Specific work of extrusion at 15°C, kgcm/g

RW - Residual specific work, %

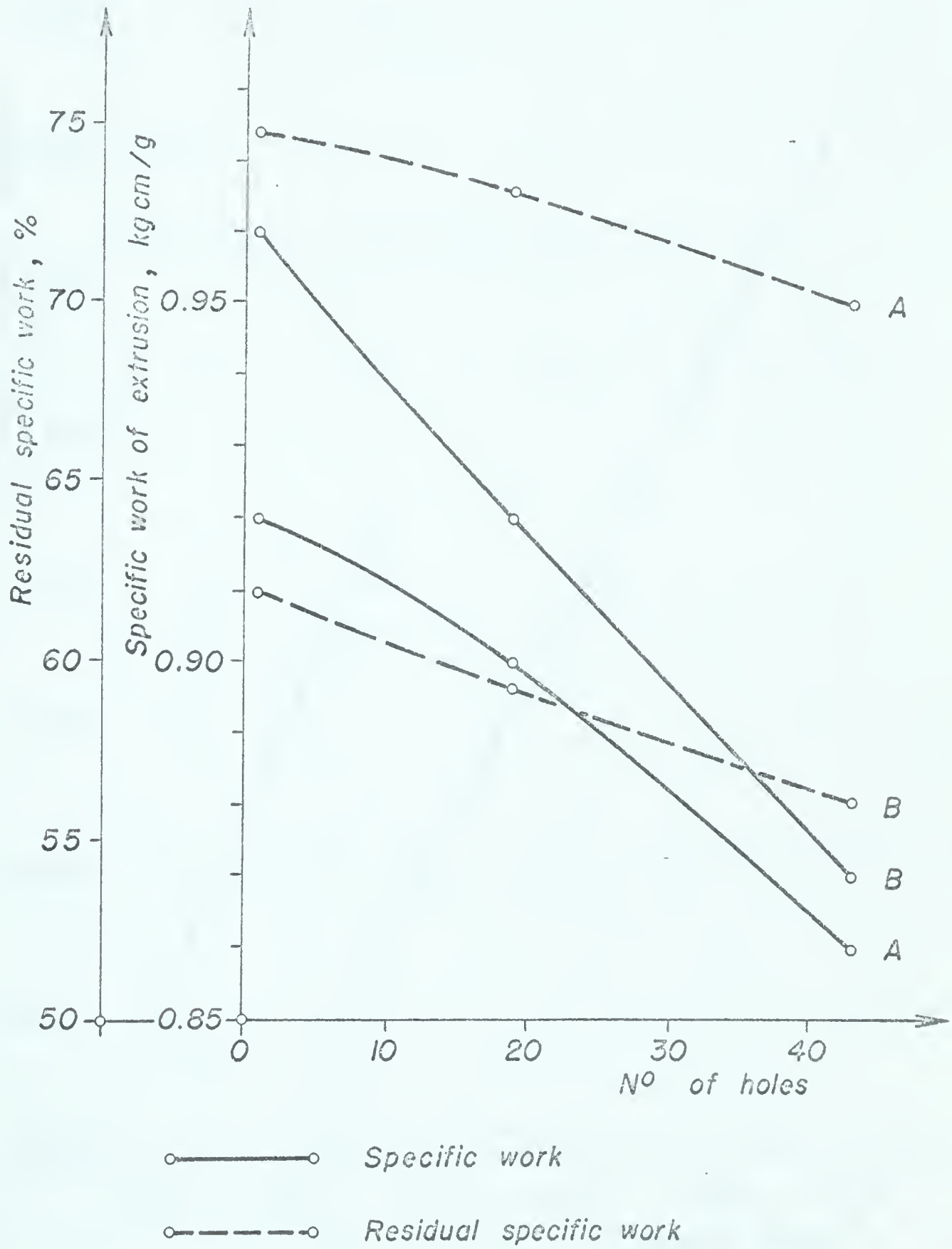


Fig. 15. Relationship between mechanical working and work of extrusion and residual specific work

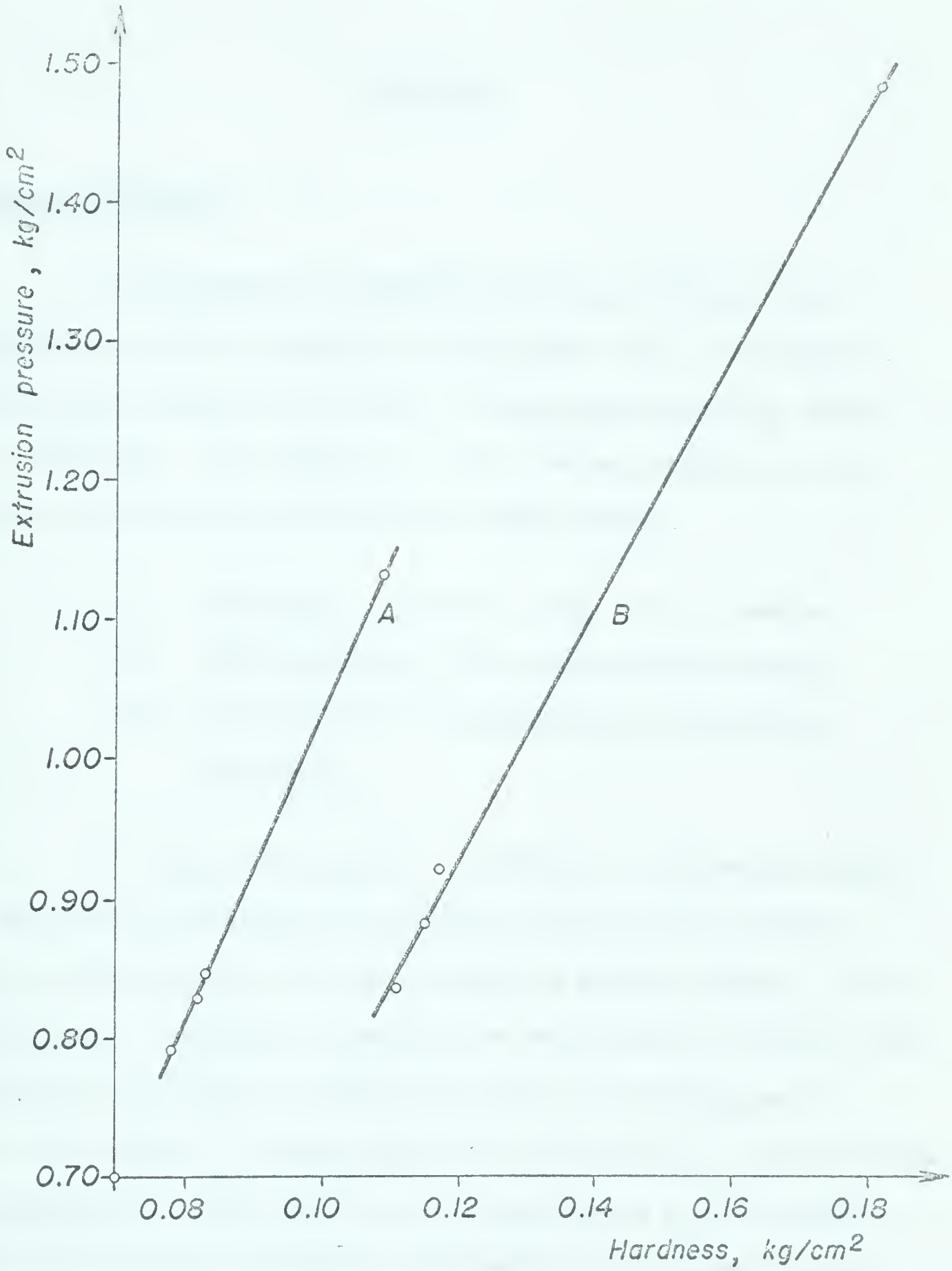


Fig. 16. Relationship between hardness and extrusion pressure

DISCUSSION

Mechanical working

The influence of mechanical working on structure and consistency is well recognized at the present time. Each type of working that subjects the butter to a shearing stress will affect its consistency. The magnitude of this change depends on several factors and they can be divided into three groups:

(i) The amount of work per weight unit of sample

(ii) The consistency of the sample before working

(iii) The intensity of the shearing stress induced by working.

(i) The work input is very difficult to measure because of unavoidable dissipation of mechanical energy during working, such as transformation into heat energy and kinetic energy. It is not possible, therefore, to measure the work input in absolute units and only a description of conditions during the working can be made. The number of strokes made with a roller (51), or the duration of kneading (67) were reported as characteristics of work applied, which is obviously insufficient information about the work input.

The mechanical treatment of butter was done by means of a modified meat grinding machine, using three different perforated plates. No exact figures can be reported on the work input, the only data available are the power consumption (180 W), the speed of

the auger (50 r.p.m.), and the flow of butter through the machine (100 g/min.).

The hardness reduction was almost constant (Tables 2 and 3, and Fig. 11) and only a slightly greater reduction was observed when the number of holes in the perforated plate was increased. This indicates that instead of a perforated plate, a screen would have a more pronounced effect on hardness reduction, other factors being equal.

A higher work input will obviously lead to a more complete destruction of the three-dimensional crystal network, and therefore, to a greater hardness reduction.

(ii) The consistency before mechanical working had a definite influence on the change in consistency. The sample series with a high initial hardness (B - continuously made butter) showed a work softening of 70% at 5°C, whereas the sample series with a lower initial hardness (A - conventionally made butter) under the same conditions showed a work softening of 50% (Fig. 11). This indicates that the difference in initial hardness (0.411 kg/cm^2, sample A and 0.895 kg/cm^2, sample B) is not only a consequence of the difference in solid fat content. It is more likely due to the different types of crystals and the formation of a three-dimensional network of different strength. Large crystals, in the continuously made butter with a higher degree of mechanical interlocking, produce a stronger network which results in a higher resistance to penetration. After mechanical working, the three-dimensional network almost disappears, and the concentration of the solid phase remains as the only factor which influences the hardness. This can easily be seen

by comparison of the hardness values of samples A and B before working and during the recovery period (Tables 2 and 4). The hardness ratio of samples B and A dropped from 2.16, before working, to 1.28 one day after working, with a subsequent increase during the recovery period to 1.50 and 1.60 after 8 and 15 days respectively, which is due to the formation of a new three-dimensional crystal network.

(iii) The most important factor which influences the change of structure and consistency is the magnitude of the shearing stress to which the butter is subjected during mechanical working.

It is a well-established fact that shearing stress is directly proportional to the rate of shear, although with plastic substances proportionality is not linear as with Newtonian fluids. A higher rate of shear will produce a greater change in consistency and vice versa. The higher rate of shear can be produced by an increased flow velocity or by a faster-moving rotor.

The number of holes in the perforated plate did not greatly affect the consistency. It should be pointed out, however, that before passing through the perforated plate the butter has already been subjected to a strong kneading by the auger, and this might imply that the work input introduced by the auger was greater than that of the perforated plate. It is possible that the number of holes would have a greater influence on consistency when applied alone, as the case in the texturator part of the continuous buttermaking machine.

Thixotropic change during working and recovery

The destruction of the three-dimensional crystal network during mechanical working could be assumed to be a reversible process although the high apparent viscosity, which appears in the proximity of the yield point, might delay or prevent a complete recovery. An extreme example is the case of molten glass, where high viscosity restricts the movement and orientation of particles to such an extent that crystallization is impossible. However, at high temperatures (above 20° - 25°C), when the solid fat content and the apparent viscosity are low, an almost complete recovery has been reported (67, 68).

Mechanical working which produces a high rate of shear when applied to a butter containing large crystals causes the destruction of the crystal network, and a disintegration of a certain amount of crystals and this is an irreversible process. Such was the case when sample B was subjected to mechanical working.

It is evident from Fig. 13, that 15 days after mechanical working the recovery of hardness of sample A was approximately 55% of the initial hardness, whereas sample B recovered 37 - 40%. The residual hardness of sample B, one day after working (30%), indicates that a certain amount of crystals was disintegrated during mechanical working. Sample A showed a decrease in hardness of 50%, which indicates that a smaller amount of crystals (if any) was disintegrated during mechanical working.

The intensity of mechanical working to which samples A and B were subjected was the same, and the slower recovery of sample B shows that some irreversible changes during mechanical working were involved, probably the partial disintegration of large crystals.

Influence of extrusion on consistency

The process of extrusion may be considered as a type of mechanical treatment. A velocity gradient, and therefore a certain rate of shear, is generated by the acceleration of the specimen, from the velocity of the extrusion plunger to the velocity of the extruded material. Although the velocities of the plunger and the sample are known (in this case, 10 cm/min. and 330 cm/min.), it was not possible to determine the length of space in which acceleration took place, and therefore the numerical value of the velocity gradient is not known. In spite of this difficulty, extrusion appears to be a more convenient method than any kind of kneading because, in the case of extrusion the force or pressure can be measured, and therefore the work of extrusion can be expressed in absolute units.

A typical extrusion diagram of butter made with the modified shear press is shown in Fig. 10. The diagram consists of two principal parts.

Part AB represents a rapid build-up of load necessary for the initial compression of the sample. In this phase, the sample completely fills the extrusion die. The slope of this line depends on the speed of plunger and the rate of extrusion.

Part BC represents a steady-state phase. The total extrusion force decreases linearly because the contact area between the sample and the walls of the extrusion die responsible for friction also decreases. At the end of the extrusion stroke, the extrusion force drops almost immediately to zero (part CD) which indicates that the elasticity of the sample is negligible.

The magnitude of the extrusion force at the end point C represents the force necessary for extrusion and the force arising from the friction of the plunger. The area in the diagram denoted by A_{fs} represents the work necessary to overcome the friction of the sample. The average friction of the extrusion plunger is shown as the area A_{fp}. This work was determined separately. The area denoted by A_e thus represents the work necessary for extrusion of the sample.

Extrusion had a similar affect on hardness (Table 5 and Fig. 14) as had the mechanical working. The hardness decrease, after extrusion at 15°C (extrusion softening), of sample B was 40% - almost the same as in the case of mechanical working (work softening) which was 36 - 39%, measured at 15°C. A somewhat greater difference was obtained after extrusion of sample A. The extrusion softening was 10 - 13%, whereas the work softening for the same sample was 24 - 28%.

Unlike mechanical working, it was possible in this case to calculate the exact amount of work used during the extrusion from the extrusion diagram. It can be seen from Table 6 and Fig. 15 that the specific work of extrusion was influenced by previous mechanical

working. The decrease in specific work of extrusion was 38 - 44% for sample B, and 25 - 30% for sample A, indicating again that mechanical treatment had a greater influence on the sample with the higher initial hardness.

An equal amount of specific work of extrusion (0.92 kg. cm/g) was required for samples A-01 and B-19, although there was a difference in hardness: 0.083 kg/cm^2 and 0.115 kg/cm^2.

It can be assumed that the specific work of extrusion or the extrusion pressure is proportional to the shearing stress, and the rate of extrusion to the rate of shear. In this particular case the apparent viscosities of these samples would be identical because the rate of shear was constant during all experiments ($r = 33$). This does not necessarily mean that the consistency of these samples is also identical, as is indicated by comparison of the samples with extrusion pressures of 0.85 and 0.88 kg/cm^2. The equality of apparent viscosities at one rate of shear does not necessarily mean that the flow properties are identical under different conditions.

The relationship between hardness and extrusion pressure is given in Fig. 16. An interesting point is that the one pressure of extrusion will produce equal rates of flow of two samples which differ in hardness.

The explanation for this phenomenon might be that not only hardness but also other rheological properties influence the magnitude of the extrusion pressure. These could be apparent viscosity,

yield value, modulus of elasticity, and shear modulus. At the present time, no definite correlation among these has been established.

The complete definition and description of consistency of a plastic fat is impossible without a knowledge of all rheological properties that influence the consistency.

To avoid different descriptive and often incomplete definitions of consistency, it is necessary to choose and define such rheological properties which may be measured and expressed in absolute units. This seems to be the only accurate way to solve the complex problem of the rheology of plastic fats.

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